Naval Submarine Medical Research Laboratory
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UPWARD EXCURSION LIMITS FROM AIR SATURATION AT 5 ATA

by

James W. Parker

Naval Medical Research and Development Command
Pesearch Work Unit No. 63713N M0099.01A-5012

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SUMMARY PAGE

THE PROBLEM

To establish upward excursion limits from air saturation at 5 ATA (132 FSWG) which could be used in pressurized submarine rescue.

THE FINDINGS

An upward excursion from 5 ATA (132 FSWG) to 3.24 ATA (74 FSWG) can safely be made.

APPLICATION

The findings can be utilized in submarine rescue operations where the disabled submarine is internally pressurized.

ADMINISTRATIVE INFORMATION

This research was carried out under Naval Medical Research and Development Command Work Unit No. 63713N M0099.01A-5012, "Medical Problems Associated with Pressurized Submarine Rescue." It was submitted for review on 14 December 1988, cleared for publication on 19 January 1989, and designated NSMRL Report No. 1127.

Abstract

Present USN submarine rescue capability makes a prolonged exposure of the submarine crew to hyperbaric air a distinct possibility. The exposure may be to pressures as great as 5 atmospheres absolute (ATA), and for periods of time of up to 72 hours. A series of experimental dives were conducted to establish the safe, upward excursion from 5 ATA (132 FSWG). That is, the maximum, immediate reduction in pressure which these individuals can safely tolerate. This specifies the required pressure in the compartment of a mother submarine to which the rescued personnel would be transferred. In order to minimize the effects of pulmonary oxygen toxicity, the limits first were established using a nitrox equivalent of air at 5 ATA. The upward limit from 4.36 ATA (111 FSWG) was found to be 2.97 ATA (65 FSWG). Once this limit had been set, a series of dives were conducted to test this up limit from standard air at 5 ATA. This final series tested the upward excursion from air saturation at 5 ATA to 3.24 ATA (74 FSWG). There were no cases of decompression sickness during the 24 hours following the upward excursion. It was concluded that this upward excursion could be recommended to the fleet for possible use in submarine rescue operations.

Introduction

Present USN submarine rescue capability makes a prolonged exposure of the submarine crew to hyperbaric air a distinct possibility. The exposure may be to pressures as great as 5 atmospheres absolute (ATA), and for periods of time of up to 72 hours. Although tested decompression schedules are now available, the practical application of such schedules requires some untested maneuvers. Specifically it would be particularly advantageous to immediately decompress the survivors to some lesser pressure, so that a mother submarine would not have to pressurize its forward compartment to the full saturation depth. The limits for such unlimited duration ascending excursions from air saturation up to 5 ATA are only theoretical and there is no agreement among investigators.

Survivors from a pressurized, distressed submarine who have been rescued by the Deep Submergence Rescue Vessel (DSRV) must be transferred either to a surface vessel (ASR type) or to a mother submarine (MOSUB). Previous work at this Laboratory in the SUREX series (1) addressed the necessary transfer procedures if an ASR were to be used. It is likely that a MOSUB will be used since they are more numerous and are deployed in both the Atlantic and Pacific fleets. In this case a surface decompression procedure will not be required since a pressurized transfer into the MOSUB forward compartment from the DSRV is possible. Although the MOSUB forward compartment is capable of being pressurized to about 4 ATA, it is desirable to pressurize this space as little as possible because equipment could be damaged by the increased pressure over the normal 1 ATA, and also because of the fire hazard due to the increased oxygen partial pressure. It would, therefore, be preferable if the survivors could be transferred into the compartment at a lower pressure than that in the DSRV/distressed submarine. Thus, it is important to know the magnitude of the rapid pressure reduction the survivors in the DSRV can safely tolerate from a variety of saturation pressures. After an appropriate period of time is spent at this new, lower pressure, they must be able safely to tolerate the final, more conventional decompression to surface pressure of 1 ATA. In addition to reducing the pressure the MOSUB forward compartment must withstand, this step decompression also has the advantage of immediately reducing the partial pressure of oxygen which may allow stabilization or recovery from any existing pulmonary oxygen toxicity which may have developed during a prolonged exposure to hyperbaric air in the distressed submarine.

Research Design and methods

Three sets of experiments were undertaken in an attempt to define the relationship between saturation pressure and maximal ascent.

The first, and shallowest point, was addressed by the MINISAT/ISLANDER (US/UK collaborative effort) experiments. In the MINISAT series (2), 34 healthy human subjects were exposed to shallow air saturation for 48 hours [1.77 ATA (25.5 FSWG) N=19; 1.89 ATA (29.5 FSWG) N=15] and then decompressed to 1 ATA (0 FSWG) in about two minutes. No subject of the 19 directly ascending from 25.5 FSWG was diagnosed as having decompression sickness (DCS), but 4 of 15, directly ascending from 29.5 FSWG were diagnosed and treated for DCS, all of which were Type I.

This report covers the two sets of related experiments investigating the "worse case" scenario of saturation at 5 ATA (132 FSWG). The first, AIRSAT-5, was designed to establish the safe, upward excursion from a nitrox saturation at a depth equivalent to 132 FSWG. This approach was taken in order to arrive at an upward excursion limit without exposing the subjects to the discomforts of pulmonary oxygen toxicity, which after 48 hours would become quite apparent (3), thus limiting potential problems only to that of DCS and related symptomatology. Once this upward excursion limit has been established from nitrox saturation, then this excursion limit was tested from an air saturation at 132 FSWG. This second series was named AIRSAT-6.

Subjects

The subjects were Navy and Naval Reserve divers who had not been subjected to pressure for at least two weeks previous to the experiment. Upon reporting, their most recent physical examination was reviewed for any duty involving experimental diving within one year. Also reviewed was their interval medical history since their last diving physical examination. Each diver received an electrocardiogram, blood and urine analysis, a complete pulmonary function battery including diffusion capacity, and a pre- and post-dive examination by an Undersea Medical Officer.

The experimental protocol was approved by the Laboratory Committee for the Protection of Human Subjects. Informed consent was obtained from each subject prior to undergoing pre-dive testing and training, and again prior to being confined in the chamber.

Table 1. AIRSAT-5 Subjects N = 33

	Mean	S.D.
Age (yrs)	31.36	4.72
Height (cm)	174.45	6.64
Weight (Kg)	82.08	10.68

Table 2. AIRSAT-6 Subjects N = 13		
	Mean	S.D.
Age (yrs)	30.42	4.85
Height (cm)	174.76	4.76
Weight (Kg)	82.38	12.24

Facility

All exposures were performed in a large, double-lock, steel hyperbaric chamber located at the Naval Submarine Medical Research Laboratory in Groton, Connecticut. It is cylindrical, approximately 3 meters in diameter, and approximately 9 meters in length, allowing uncramped habitability for up to five subjects at a time. Temperature was adjusted to subject comfort, while humidity generally stabilized at about 60%. Carbon dioxide was removed through the life support loop with installed scrubbers filled with Sodasorb. The CO_2 level was continuously monitored and never allowed to exceed 0.5%, surface equivalent. All exposures were dry.

Decompression to the Surface

After a 24-hour hold following the direct upward excursion, decompression to the surface was initiated with the pO_2 maintained at 0.4 ATA; the rate was calculated following the method of Vann (3). The formula used in the calculations is:

$$\text{Ascent Rate} = K(PiO_2)$$

Where K is an empirically derived constant equalling 5, and the PiO_2 is in ATA. The ascent rate is minutes per foot.

This results in the following tables where the travel is in increments of one foot:

Table 3. AIRSAT-5 Decompression Schedule	
Depth	Rate
85 - 30 FSWG	30 min/ft
29 - 20 "	35 "
19 - 10 "	44 "
9 - 0 "	58 "

Table 4. AIRSAT-6 Decompression Schedule	
Depth	Rate
74 - 70 FSWG	18 min/ft
69 - 65 "	19 "
64 - 60 "	20 "
59 - 55 "	22 "
54 - 50 "	23 "
49 - 45 "	24 "
44 - 40 "	26 "
39 - 35 "	28 "
34 - 30 "	30 "
29 - 25 "	33 "
24 - 20 "	36 "
19 - 15 "	39 "
14 - 10 "	44 "
9 - 5 "	50 "
4 - 0 "	57 "
Total decompression time: 38 hours, 47 minutes	

AIRSAT-5

The AIRSAT-5 exposures consisted of 48-hour exposures to nitrogen-oxygen (near normoxic) with a nitrogen partial pressure of 3.95 ATA, which is equivalent to that of air at 5 ATA (132 FSWG). Figure 1 shows the dive profile. Thus using a PiO_2 of 0.4 ATA, the nitrox equivalent depth is 111 FSWG or 4.36 ATA. Therefore, the subjects were compressed to 111 FSWG where they remained for 48 hours in order to achieve saturation. After the 48-hour hold they were decompressed at a rate of 60 feet per minute to the upward limit being tested.

AIRSATs 5A and 5B were run with three diver-subjects each for a total of six with the upward excursion being from 4.36 ATA (111 FSWG) to 3.12 ATA (70 FSWG). After the jump to 70 feet, the subjects were carefully monitored for 24 hours before commencing the decompression to the surface. None of the six subjects reported any symptoms of DCS either after the upward excursion or during the decompression to the surface.

Since all subjects were "clean" on these dives, it was decided to increase the upward excursion to 2.82 ATA (60 FSWG). Therefore, AIRSATs 5C and 5D were run, again with three subjects each. The protocol was the same as before with the exception of the greater upward excursion. None of the subjects reported symptoms of DCS during the 24 hours following the excursion. However, one subject did report symptoms of DCS at 25 feet on the way to the surface and was treated. It was felt that the DCS in this subject was not due to the upward excursion, but as a result of the decompression to the surface. This subject was older (39 years) and in poorer physical condition than the other five.

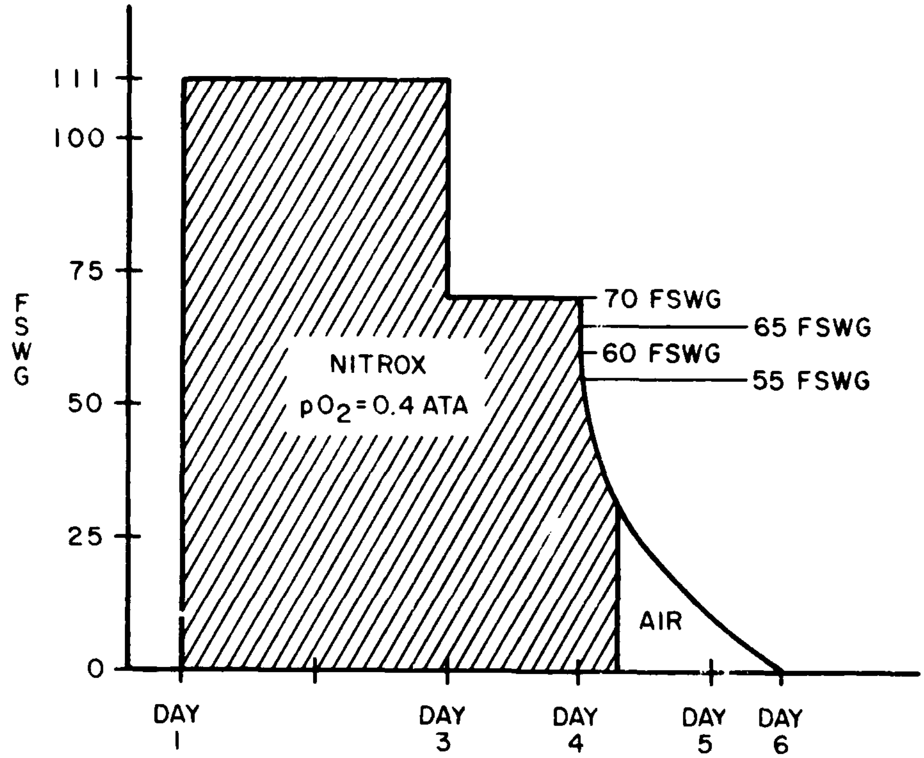

Figure 1. Dive Profile: AIRSAT-5 Series

Since it appeared that this excursion was "safe", it was decided to try an additional five feet. AIRSAT-5E, with four diver-subjects, then was carried out with the direct, upward excursion from 4.36 ATA (111 FSWG) to 2.67 ATA (55 FSWG). Shortly after arriving at the 55-foot depth, one diver began complaining of symptoms indicative of Type I DCS. Shortly thereafter, two additional divers began complaining, and it was decided to abort the dive. The divers were recompressed to 85 FSWG, where relief was obtained. After a 24-hour hold, decompression to the surface was initiated and completed without incident.

Now that DCS had manifested itself at the 55-foot level, it was decided to return to the 60-foot limit with additional subjects in order better to establish a limit. AIRSATs 5F and 5G were then run with four diver-subjects each, again following the same protocol as before. In AIRSAT-5F, one diver complained of DCS nearly six hours after the jump to 60 feet and he was successfully treated with three cycles of breathing oxygen. In AIRSAT-5G, one diver complained of pain nearly four hours after the pull and was put on the O_2 treatment. Three hours later, a second diver complained of pain. The decision then was made to recompress all four divers. Complete relief was observed at 90 FSWG. Additionally, two divers exhibited symptoms of Type I DCS at 11 feet during the decompression to the surface; decompression was stopped and the four were recompressed to 41 FSWG, the depth of relief. Final decompression was uneventful with no further problems. At this point it looked like the 60-foot upward limit was right on the "edge".

In order to establish a reasonably "safe" upward excursion limit, the decision was made to run additional dives with the excursion limit set at 2.97 ATA (65 FSWG). AIRSATs 5H, 5I, and 5J were carried out with a total of nine diver-subjects. There were no cases of DCS during the 24-hour hold after reaching the excursion depth of 65 feet. There was on one dive, however, one case of Type I DCS at 14 feet during the decompression to the surface. At this point, after 10 experimental dives carried out over a two-year period, it was concluded that the limit had been established and that it was time to establish the feasibility of this limit on standard air rather than nitrox.

Table 5 summarizes the occurrence of DCS during the AIRSAT-5 series. There were no cases of DCS other than shown in the table. It should be emphasized that, statistically, the small samples used may not give a true picture of the incidence of DCS in decompression from nitrox saturation. Eighty to 100 subjects per series would be required to determine the incidence of DCS with a standard error less than 5%.

Table 5. Decompression Sickness: AIRSAT-5

Depth	N	DCS
111 > 70	6	0 at 70 FSWG
111 > 60	14	3 at 60 FSWG 1 at 25 FSWG 1 at 11 FSWG
111 > 55	4	3 at 55 FSWG
111 > 65	9	0 at 65 FSWG 1 at 14 FSWG
Surface	33	(none)

Doppler monitoring for venous gas emboli was carried out on only a few dives due to equipment problems. With the limited amount of doppler data available, very little can be said with regard to the predictive value of the presence or absence of venous bubbles.

AIRSAT-6

As a result of discussions held in the Tri-Partite Conference held at NSMRL in June 1987 (4), it was agreed that a 48-hour hold probably was unrealistically short in terms of the length of time necessary for "rescue" to begin after the accident. Seventy-two hours was felt to be more realistic. Therefore the time at depth prior to the upward excursion was changed to 72 hours. The AIRSAT-6 exposures started the same as with AIRSAT-5, as shown in Figure 2. This dive was physiologically equivalent to the AIRSAT-5 series except that the total time of exposure to elevated pressure before the upward excursion was 72 vice 48 hours. The divers were compressed to 4.36 ATA (111 FSWG) on a nitrox breathing mix with a pO_2 of 0.4. They were held at 111 FSWG for 60 hours, after which the atmosphere was changed to standard air (pO_2 = 1.05) and at the same time the divers were further compressed to 5 ATA (132 FSWG). This was done in order to minimize the effects of pulmonary oxygen toxicity. The partial pressure of nitrogen in the nitrox mix at 111 FSWG is the same as that of standard air at 132 FSWG. After a 12-hour hold at 132 FSWG on air, an immediate ascent at 60 feet per minute was made to 3.24 ATA (74 FSWG) which is the air equivalent depth of the 65 FSWG established in the AIRSAT-5 series. As before, the divers were held at 74 FSWG for 24 hours after which decompression to the surface was initiated. Figure 2 shows the dive profile.

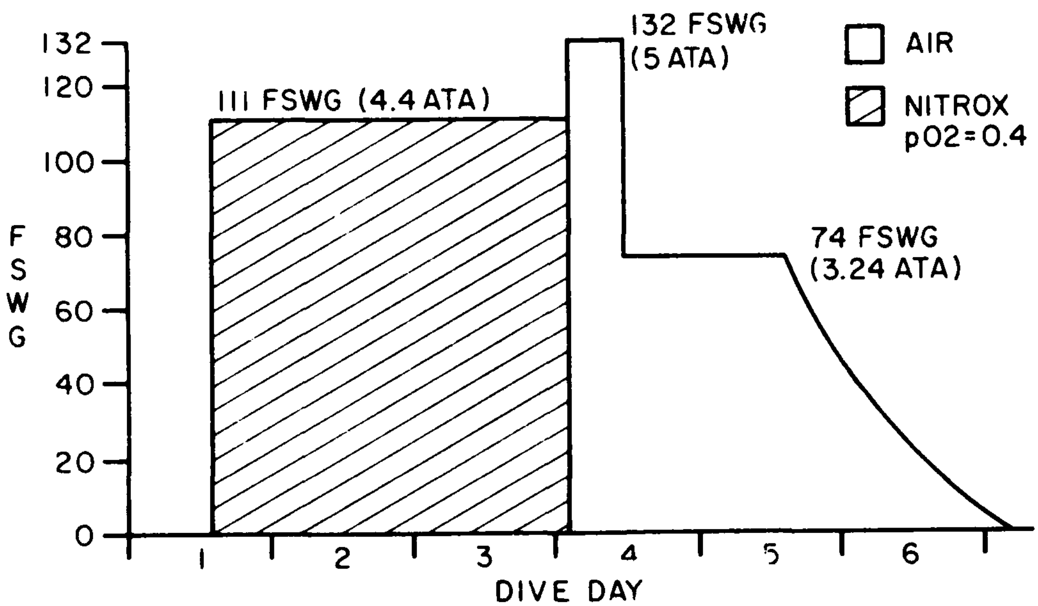

Figure 2: Dive Profile: AIRSAT-6 Series

In this series there were no cases of DCS either following the immediate ascent to 74 FSWG or during the final decompression to the surface from that depth as shown in Table 6. There were minimal complaints of the effects of pulmonary oxygen toxicity. Doppler monitoring (precordial only) showed minimal venous gas emboli.

Table 6 Decompression Sickness: AIRSAT-6		
Depth	N	DCS
132 > 74	13	0 at 74 FSWG
74 > 0	13	(none)
Surface	13	(none)

The decompression schedule, Table 4, followed for decompression to the surface from 74 FSWG was computed also by the method of Vann (3). However, the interval between rate changes was shortened from 10 to 5 feet. It is possible that the shortened interval is, at least, partially responsible for the absence of DCS in the decompression from 74 FSWG to the surface.

Discussion

The purpose of this series of experimental dives was to establish a safe, upward excursion from air saturation at 5 ATA (132 FSWG). This upward excursion then could be used in a submarine rescue scenario: the personnel evacuated from a disabled submarine by the DSRV would be transferred to the bow compartment of a mother submarine where the amount of pressurization over the 1 ATA existing in the submarine could be held to a minimum. This information should be included in a manual for pressurized submarine rescue and distributed to those fleet units who might be expected to be involved in such a rescue, e.g., ASRs and SSN-637 class submarines designated as possible MOSUBs. As has been pointed out in this report, the numbers on which the conclusions are reached are very small and thus any generalizations to other saturation diving operations should be taken with extreme caution. These experimental dives should be repeated using a significantly greater subject population.

Another caveat is that the subjects on which the conclusions of this report are based are Navy divers. In the rescue situation these upward excursions will be made by submarine personnel, most of whom are not trained divers accustomed to breathing at elevated pressure levels with the associated sensations. It is also possible that the personnel being rescued may be injured or have been exposed to breathing atmospheres with higher levels of carbon dioxide and which may contain toxic gases resulting from possible fire or other problems associated with the submarine being in distress. These factors certainly could have a deleterious effect on the safety of the tables used in this study. The on-scene commander of the rescue operation would have to take these factors into account in his decision-making process.

Summary and Conclusions

An upward excursion from air saturation at 5 ATA (132 FSWG) can be made to 3.24 ATA (74 FSWG) with a minimum risk of decompression sickness. This would be useful in a submarine rescue scenario where the submarine has an elevated internal pressure greater than 1 ATA (0 FSWG), where the rescue is being effected by the DSRV, and where the rescued personnel are being transferred to the bow compartment of a mother submarine for eventual decompression to surface pressure. This upward excursion prior to transfer means that the submarine compartment will not have to be pressurized to as great a depth as might otherwise have been necessary.

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Present USN submarine rescue capability makes a prolonged exposure of the submarine crew to hyperbaric air a distinct possibility. The exposure may be to pressures as great as 5 atmospheres absolute (ATA), and for periods of time of up to 72 hours. A series of experimental dives were conducted to establish the safe, upward excursion from 5 ATA (132 FSWG). That is, the maximum, immediate reduction in pressure which these individuals can safely tolerate. This specifies the required pressure in the compartment of a mother submarine to which the rescued personnel would be transferred. In order to minimize the effects of pulmonary oxygen toxicity, the limit first were established using a nitrox equivalent of air at 5 ATA. the upward limit from 4.36 ATA (111 FSWG) was found to be 2.97 ATA (65 FSWG). Once this limit had been set, a series of dives were conducted to tes this limit from standard air at 5 ATA. This final series tested the upward excursion from air saturation at 5 ATA to 3.24 ATA (74 FSWG). There were no cases of decompression sickness during the 24 hours following the upward excursion. It was concluded

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that this upward excursion could be recommended to the fleet for possible use in submarine rescue operations.